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Research Article

Status assessment of non-native terrestrial species in Antarctica

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Abstract

Antarctica has been subject to direct human activity for a little over 200 years. In recent decades, the combination of sharp increases in human activity and regional climate change, particularly around the Antarctic Peninsula and Scotia Arc, have placed the terrestrial and freshwater environment under increased threat of non-native species introduction and establishment. Policymakers, including those on the Antarctic Treaty Consultative Meeting's Committee for Environmental Protection, need accurate and up-to-date information on the presence and status of non-native species within Antarctica upon which to base their decision-making. Here we collate available information to consider the status of known non-native species in the terrestrial Antarctic, and how this has changed in the past decade. Of known establishments, we found 46% to have been deliberately introduced during historical transplant experiments and subsequently removed, 36% were non-experimental introductions, and 18% only survive(d) synanthropically (i.e., associated with Antarctic facilities). All non-native species currently established in the natural Antarctic environment are located in either the Antarctic Peninsula, South Shetland Islands or South Orkney Islands (i.e., the maritime Antarctic region, with none in the continental Antarctic), with invertebrate species dominating. Most of the currently established non-native species have now been present for more than a decade, though the more recent appearance of non-native flies in station sewage treatment plants and their expansion into the Antarctic environment is a major cause for concern. While there has been some success in eradicating introduced plants, management of introduced invertebrates in the natural environment has largely not been attempted. Considerable scope exists for the Antarctic Treaty Parties to better coordinate non-native species management across the invasion continuum.

Key words: Alien, biological invasion, biosecurity, Committee for Environmental Protection, environmental management, risk

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Introduction

Humans first arrived in Antarctica in the 1820s and, in the process of travelling to the region, almost certainly brought the first non-native species with them (Headland 2009). Since that time, and likely correlated with the level of human activity, the number and diversity of introduced non-native species in the region has grown (Frenot et al. 2005; Hughes et al. 2015). For the purposes of this study, a non-native

species is defined as a species existing beyond its natural dispersal range, transported either deliberately or unintentionally by human activity, and an invasive species is a non-native species that expands its distribution following establishment in a newly colonised area and has a negative impact upon native species and/or ecosystem function (Blackburn et al. 2011; Antarctic Treaty Secretariat 2019). The progressive extension of national Antarctic programme footprints across the continent, including the construction of new research stations, plus the expansion of the tourism industry, particularly in the Antarctic Peninsula region, is likely to have increased opportunities for species introductions, as well as for the intra-regional transfer of species native to different regions in Antarctica (also termed as 'native-alien populations', see Nelufule et al. 2022) (Pertierra et al. 2017a; Brooks et al. 2019; Hughes et al. 2019). For much of Antarctica the extreme environmental conditions and scale of geographical isolation, compared to many other parts of the planet, have provided a barrier to establishment of non-native species (González-Herrero et al. 2024). However, climate change has already ameliorated environmental conditions in the Antarctic Peninsula region (which has warmed by c. 3 °C since the mid-20th Century) and the warming now detected across other areas of the continent is predicted to accelerate (Bracegirdle et al. 2019; Turner et al. 2019; Clem et al. 2020). Under these rapidly changing circumstances the risk of species introduction, establishment and subsequent transition to invasive status is a major cause for concern (Convey and Peck 2019; Duffy and Lee 2019; Lee et al. 2022a).

The Committee for Environmental Protection (CEP), created under the terms of the Protocol on Environmental Protection to the Antarctic Treaty (also known as the Environmental Protocol or Madrid Protocol), is the body formally tasked with the provision of advice to the Antarctic Treaty Consultative Meeting (ATCM) on environmental issues concerning the Antarctic Treaty area (i.e., all land, sea and ice areas south of latitude 60°S), as well as relating to dependant and associated ecosystems north of that latitude (Sánchez and McIvor 2007). The remit of the CEP includes non-native species issues, with policy advances including the development of the CEP Non-native Species Manual, which was first drafted in 2011 and underwent a major revision in 2016 (Antarctic Treaty Secretariat 2019), and the inclusion of non-native species in the CEP Climate Change Response Work Programme (Antarctic Treaty Secretariat 2024a) and CEP Five-year Work Plan (Antarctic Treaty Secretariat 2024b). To build on this work, policymakers rely upon accurate, apolitical and up-to-date information upon which to base their decision-making. A challenge for researchers is how best to provide this information (McIvor 2020; Hughes et al. 2022, 2023)

A number of studies have attempted to consolidate records of mostly terrestrial and freshwater non-native species in the Antarctic Treaty area, with some also extending to the sub- and wider peri-Antarctic islands. Few putative records of introductions of non-native marine species exist in the Antarctic Treaty area, with virtually no confirmed instances of establishment in either the short or the longer term (McCarthy et al. 2019). Smith (1996) provided a chronological account of all known experimental and accidental introductions of higher plants to the Antarctic Treaty area and discussed the associated impacts and conservation issues. Twenty years ago, Frenot et al. (2005), in their influential synthesis, recorded instances of plant, vertebrate, invertebrate, microbial and marine species introductions across the wider Antarctic region (i.e., also including the core sub-Antarctic islands) and placed these into the context of a rapidly changing environment. In 2012,

Greenslade and co-authors produced two papers describing the non-native collembolan fauna of Deception Island (South Shetland Islands) and the sub-Antarctic (Greenslade and Convey 2012; Greenslade et al. 2012). Three years later, in 2015, and following the submission of regular updates on non-native species introductions to the CEP, Hughes et al. (2015) produced a list of species thought to be established in Antarctica at that time. Most recently, Leihy et al. (2023) produced a dataset detailing species known or inferred in the literature to have been introduced to the terrestrial and freshwater environments of Antarctica and the sub-Antarctic as well as to some lower latitude peri-Antarctic islands, although most of these records represent the latter island regions rather than the Antarctic Treaty area and do not include any explicit assessment of evidence of establishment.

In this study, we revise, update and expand the dataset of Leihy et al. (2023), focusing only on the terrestrial environment within the Antarctic Treaty area. We added 125 additional records of established non-native species and applied strict criteria to existing records to identify only established species (as distinct from those introduced but that did not establish, or that are now known to be native) which led to the removal of 103 records. We also included in our dataset additional information pertaining to the records, including geographical coordinates. We used this dataset to investigate trends and patterns in non-native species introductions and survival and assessed whether there have been any major status changes in the last decade (i.e., since the publication of Hughes et al. (2015). We intend this information to be of use to researchers, policymakers and environmental practitioners engaged in policy development and management of non-native species within the Antarctic Treaty area and beyond.

Methods

Collation of data for the database

All non-native terrestrial and freshwater species records located within the Antarctic Treaty area were within the scope of our study. Microbial introductions, except for a limited range of fungal species, were not included to any substantial degree (but see Cowan et al. 2011 and Hughes et al. 2018). As a starting point, a recently published list of introduced and invasive non-native species present in the broader Antarctic region was obtained from Leihy et al. (2023). The 218 records relating to the Antarctic Treaty area in the dataset of Leihy et al. (2023) were considered to be within the study's scope and were reassessed using a strict set of criteria to robustly identify species records that could with confidence be considered to have been anthropogenically introduced and subsequently established in Antarctica.

Records were excluded when: (i) the species is known to be native to the area of introduction; (ii) there is no evidence of establishment in Antarctica, either in the natural environment or in human-associated locations such as station buildings (e.g., the species was immediately removed or destroyed upon introduction, or there was no evidence the species had survived *in situ* and/or may have arrived in Antarctica already dead); (iii) the evidence from the source reference was too unreliable or weak for it to be included (e.g., there was no clear evidence of the introduction being human-mediated, or there was potential mis-identification); (iv) the species were vertebrates that were deliberately introduced for indoor experimental purposes (e.g. hamsters (Stewart 1990)), as pets (e.g., rabbits and cats), for food (e.g., pigs, sheep,

cows), or as working animals (e.g., horses, dogs); (v) the record was of experiments where plants were cultivated indoors; (vi) the record was for plant propagules, but without the presence of developing or mature plants; or (vii) duplicate records. Application of these criteria resulted in 103 records being rejected from the published list of Leihy et al. (2023). The remaining 115 records were then supplemented with a further 125 additional records that satisfied the criteria which were present in older primary literature or had been recently published (literature published up until May 2024 was considered). Records were identified in publications through a systematic search on Google Scholar (https://scholar.google.com/) using the search terms 'Antarctic*' and 'non-native' or 'alien' or 'invasive'. However, in almost all cases, the additional records were identified based on the bibliographies of the authors who collectively have undertaken research on Antarctic non-native species for more than 60 years. In total, the new dataset contains 240 records of non-native species establishment events in the Antarctic Treaty area. Where possible, citations were made to the original source literature, rather than to existing literature reviews, compilations or lists of Antarctic non-native species (e.g., those of Pugh 1993, 1994; Smith 1996; Headland 2012; Hughes et al. 2015). The current dataset includes species survival time (see definition below) and location coordinates for the records. The original sources were checked for each record and information was confirmed and/or further details were added. An explanation and details of the field names used in the database are provided in Table 1. Field names are consistent with Darwin Core Standards where possible (see: https://dwc.tdwg.org/; Wieczorek et al. 2012). Details of the full scientific names, including the kingdom, phylum, class, order, family and species, were based on information contained within the Global Biodiversity Information Facility (https://www.gbif.org/). The dataset and metadata for this manuscript are freely available from the UK Polar Data Centre (https://doi.org/10.5285/afeb9f5e-bd69-4e3d-9d50-e935134f4c78). The dataset was also made available to the Committee for Environmental Protection in May 2024 as an interactive online application (SCAR 2024; https://saer-non-nativespecies.data.bas.ac.uk).

The distance from each record to the nearest national operator facility and visitor landing site was computed using the COMNAP facilities database and International Association of Antarctica Tour Operators (IAATO) landing site data (available from: https://iaato.org/information-resources/data-statistics/), respectively, and the 'Near' tool in ArcGIS Pro (v3.2). As a proxy for survey effort and biological knowledge in the vicinity of the site of establishment, the average distance to the ten closest biodiversity occurrence records (i.e., records of native Antarctic species with location and observation time) was computed using the recently available ice-free terrestrial biodiversity database (Terauds et al. 2025) and the 'Generate near table' tool in ArcGIS Pro (v 3.2). R version 4.2.2 was used for data visualisation (R Core Team 2022).

Results

Spatial distribution and means of introduction

In total we identified reports of 112 non-native species that have established at some point in time at 67 sites across Antarctica (Fig. 1; Table 2). These species can be divided into three main categories, representing their means of introduction, i.e., deliberately, unintentionally and present in the natural environment, or unintentionally and present inside buildings (here termed synanthropic).

Table 1. Explanation and details of the field names used in the Antarctic Treaty area non-native terrestrial species database.

Field name	Notes
record ID	Unique identifier for each record in database
occurrence status	The species is 'present' or 'absent' within the Antarctic Treaty area, or occurrence 'uncertain'.
category of introduction	The category describes how the introduction occurred, i.e., 'deliberate experiment' (introduced for experimental purposes at the given location), 'non-experimental introduction' (unintentional introduction to the Antarctic natural environment), or 'synanthropic' (species that have been introduced to and colonised human infrastructure within the Antarctic Treaty area).
scientific name	Scientific name of the species, e.g. *Poa annua*
Authorship	The authorship of the species/taxon name, e.g. 'L.' or 'Baker, 1965'
vernacular name	Common name, e.g., annual bluegrass.
kingdom	Biological classification
phylum	Biological classification.
class	Biological classification.
order	Biological classification.
family	Biological classification.
decimalLatitude and decimalLongitude	Coordinates for each of the records were obtained using, in order of priority, (i) the original source (where many newer citations provided the exact coordinates, or where older citations provided a detailed map that could be used to determine the coordinates using Google Earth), (ii) in the case of the site being scientific infrastructure, the Council of Managers of National Antarctic Programs (COMNAP) Antarctic facilities database (https://www.comnap.aq/antarctic-facilities-information), or (iii) in the case of the site being within or close to an Antarctic Specially Protected Area (ASPA), the ASPA management plans which were available from the Antarctic Treaty Secretariat Antarctic Protected Area database (https://www.ats.aq/devph/en/apa-database), or (iv) the placename coordinates detailed in the SCAR Composite Gazetteer of Antarctica.
Location	Named location of the record as given in the reference/s.
ACBR_ID	Antarctic Conservation Biogeographic Region (ACBR; see Terauds and Lee 2016) in which the species was located.
ASPA_ID	Further information was provided on which (if any) Antarctic Specially Protected Area (ASPA) the record occurred within.
establishment means	The mechanism of introduction and/or details of the source population.
pathway	The process by which the species came to be in the given location, e.g., research or transportation of habitat material.
first observation year	The year the species was first observed at the recorded location within the Antarctic Treaty area.
eradicationStatus	Status of whether or not the species has been eradicated, and if relevant, noting if the species was removed upon conclusion of a scientific experiment, died out without human intervention, is subject to on-going eradication efforts, or is still currently present.
eradication year	The year the species was eradicated, removed, or died out (if applicable; see 'eradicationStatus').
survival time	The period the species remained viable within the Antarctic Treaty area before either dying out or being removed, which is important for identifying and understanding the most persistent biological groups and the pace of management action. The survival time was calculated as the number of years or months (as relevant) between the first observation of the species at the given location in Antarctica and January of 2024.
occurrence remarks	Including, as relevant, details of the source population, abundance, etc.
first publish year	The year the record was first published in the academic literature (as available).
references	Original references (where available) and associated references relating to the species introduction to the Antarctic Treaty area in abbreviated form. Full references are available in the 'references' csv.
Leihy_record ID	The record identification number used in Leihy et al. (2023) (where available).
CoL_Taxon ID	Catalogue of Life (https://www.catalogueoflife.org/) species identifier.

Table 2. Number of records and species allocated to each introduction category group.

No.	Group	No. of records	No. of species
1	Species introduced deliberately to the natural Antarctic environment during transplantation experiments (and then removed)	112	67[1]
2	Non-experimental introductions of non-native species to the Antarctic natural environment	87	27[2]
3	Non-experimental introductions of non-native species persisting synanthropically	41	22[3]
	Total	240	112[4]

[1] Excludes three records that had insufficient taxonomic information.
[2] Excludes five records that had insufficient taxonomic information.
[3] Excludes four records that had insufficient taxonomic information.
[4] Some species are common to more than one group.

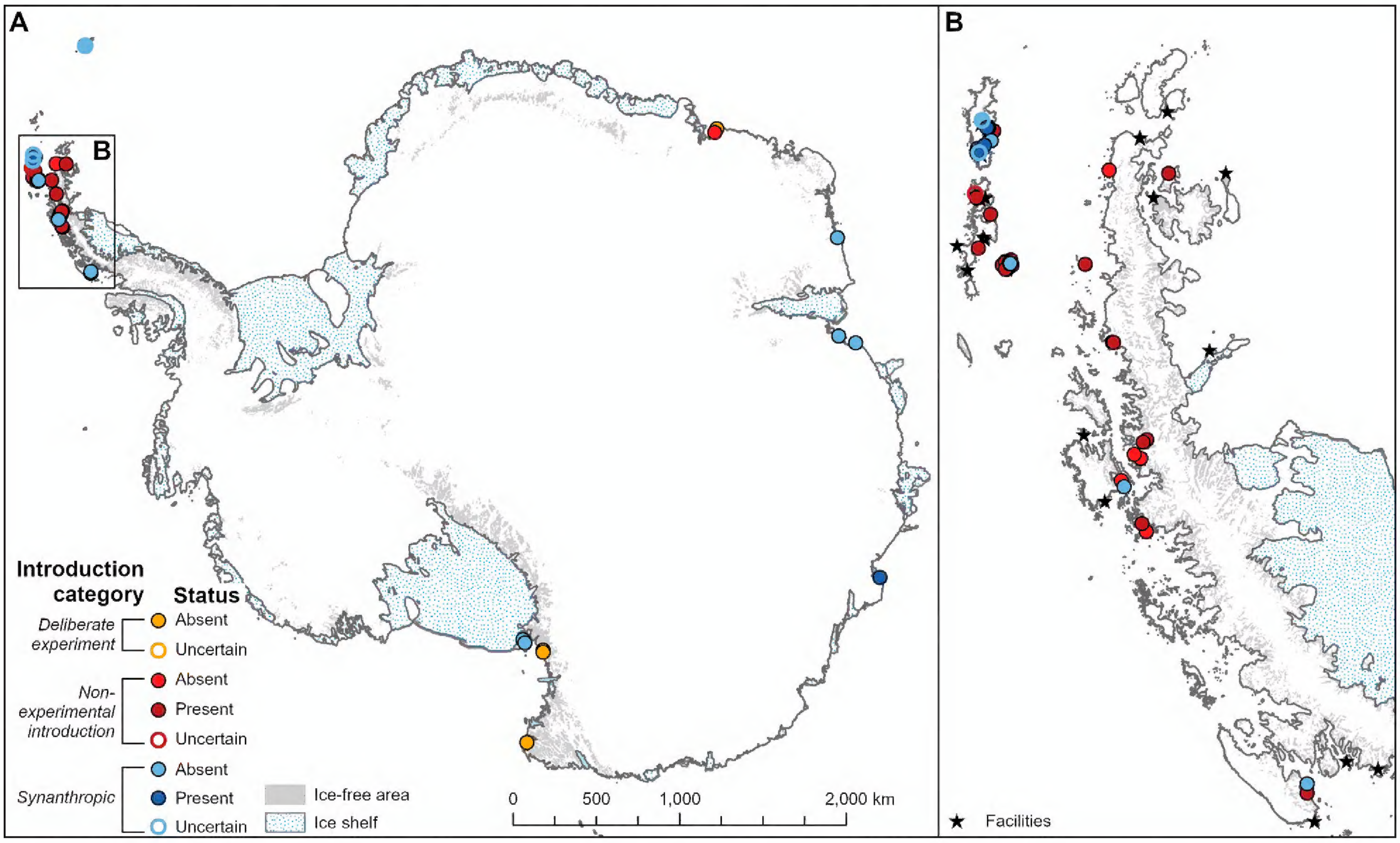

Figure 1. Distribution of non-native species records across **A** the entire Antarctic continent and **B** the northern Antarctic Peninsula. Map **B** is an inset of Map **A** and the legend in Map **A** is also relevant to Map **B**. Records are coloured by introduction category and occurrence status.

(i) Species introduced deliberately to the natural Antarctic environment during transplantation experiments

The largest group of records comprises 112 reports of at least 67 plant species (this number excludes records that had insufficient taxonomic information to identify the record to species level) that were introduced deliberately to Antarctica during transplantation experiments. Acknowledging the lack of available information for some records, as far as we can ascertain the great majority if not all deliberate introductions to Antarctica have been 'experimental introductions' (transplantation experiments) that were conducted at various times during the 20th Century. Transplantation experiments within the Treaty area involving species from outside the Antarctic would still be permitted through Annex II to the Protocol (but only under strict conditions intended to minimise the risk of long-term environmental impact). However, we are not aware of any such experiments having been undertaken in recent years (but see Câmara et al. (2021)). Most experimental species introductions were undertaken on Signy Island (South Orkney Islands), involving plants originating from the Scottish mountains (the Cairngorms), the Falkland Islands and South Georgia (Edwards and Greene 1973; Edwards 1980). However, a smaller number of reports are available from Port Lockroy (Goudier Island), Cierva Point (Danco Coast) and from the continental Antarctic sites of Cape Hallett, Granite Harbour and Syowa Station involving plants originating from, e.g., South America, Japan, the UK, or other parts of Antarctica (intra-regional transfer) (Corte 1961; Holdgate 1964; Young 1970; Smith 1996). There is no indication that any of these plant introductions remain *in situ* today, with all either dying during, or being removed at the termination of, the experiments.

(ii) Non-experimental introductions of non-native species to the Antarctic natural environment

Eighty-seven records of at least 27 species were introduced as a result of non-experimental activities. Established species in continental Antarctica were limited to only two locations, the grass *Puccinellia tenella* located very close to a refuge building c. 25 km from Syowa Station, Enderby Land, and five plant species (*Stellaria media*, *Rumex pulcher*, *Puccinellia distans*, *Oxybasis rubra* and *Alopecurus geniculatus*) at Progress II Station, Larsemann Hills; none of which remain (Russian Federation 1999; Tsujimoto et al. 2010). Records for currently surviving species are located on the western Antarctic Peninsula, the South Shetland Islands and South Orkney Islands (all within the maritime Antarctic). All but two of these records relate to invertebrate species, with the majority being Collembola or Acari at sites of a regular national Antarctic operator or tourism industry activity (e.g., see Russell et al. 2013). The two plant records relate to the presence of the invasive grass *Poa annua* in the immediate vicinity of Arctowski Station (King George Island) and the subsequent dispersal of this grass into the nearby Antarctic Specially Protected Area (ASPA) 128 Western Shores of Admiralty Bay, King George Island, South Shetland Islands (Galera et al. 2017, 2019, 2021). Reports of insects (Diptera) include *Trichocera maculipennis* on King George Island and *Eretmoptera murphyi* on Signy Island (South Orkney Islands) (Burn 1982; Hughes and Worland 2010; Volonterio et al. 2013; Potocka and Krzeminska 2018; Bartlett et al. 2020; Remedios-De León et al. 2021). The only annelid is the enchytraeid worm *Christensenidrilus blocki*, that was likely introduced to Signy Island in the same plant transplant experiment that led to the establishment of *E. murphyi* (Block and Christensen 1985).

Several non-native plant species that established in the Antarctic natural environment have been eradicated. Other than its large established population in the vicinity of Arctowski Station, King George Island, *P. annua* has been detected and eradicated, as single or small numbers of individual plants, at various locations across the Antarctic Peninsula, South Shetland Islands and South Orkney Islands (Molina-Montenegro et al. 2012, 2014; Malfasi et al. 2020), while its congener *P. pratensis* was eradicated from close to ASPA 134 Cierva Point, Danco Coast, Antarctic Peninsula in 2015 (Corte 1961; Pertierra et al. 2013, 2017b). Plants have also been eradicated from East Antarctic locations, including the five species from Progress II Station and *Pu. tenella* at a site near Syowa Station, mentioned earlier. *Nassauvia magellanica* and *Gamochaeta nivalis* were first reported from Whalers Bay in 2010 and subsequently respectively eradicated or washed away, but it was not clear if they had colonised by natural or anthropogenic means (Smith and Richardson 2011). This illustrates an important and unresolved challenge for authorities to assess when new species are discovered in the natural Antarctic environment (Hughes and Convey 2012; Malfasi et al. 2020).

(iii) Non-experimental introductions of non-native species persisting synanthropically

Our study identified 41 reports, concerning at least 22 species that have been or continue to be present synanthropically in research stations and other Antarctic facilities. However, the list of species known to have existed only synanthropically in Antarctica is probably not exhaustive, largely due to poor reporting, but does give

an indication of the variety of species capable of persisting specifically in association with research stations and other Antarctic infrastructure. Hydroponic facilities and sewage treatment plants have been particularly prone to synanthropic infestation (Hughes et al. 2005; Bamsey et al. 2015; Bergstrom et al. 2018). Of particular current concern is *T. maculipennis* which, although originally largely assumed to have been associated with station sewage systems, has spread rapidly across several research stations and is now thought to survive and reproduce in the Antarctic environment (Volonterio et al. 2013; Remedios-De León et al. 2023; Poland 2024a).

Taxonomy of recorded non-native species

Established non-native species predominantly represent a small number of taxonomic groups (Fig. 2a). The deliberate introduction of species for experimental purposes involved plants almost exclusively, resulting in the large number of records of Magnoliopsida and Liliopsida and, to a lesser degree, Polytrichopsida (Smith 1996). In contrast, while unintentional introductions of Liliopsida and Magnoliopsida were recorded, the greater number have been of invertebrates, especially representatives of Collembola, Arachnida and Insecta. It is clear that, for most plant records, the plants no longer remain (Fig. 2b). This is because either (i) these were mostly experimental introductions involving small numbers of plants that were planted in small defined areas where eradication was simple to undertake and planned at the end of the experiment, or (ii) for non-experimental introductions, recorded plants were present as single specimens or in small numbers that were readily removed. The main exceptions here are the two more extensive *P. annua* populations at Admiralty Bay, King George Island, which persist despite on-going eradication efforts (Galera et al. 2017, 2019, 2021; Poland 2024b). In contrast, invertebrates once introduced tend to persist and there are no known attempts to eradicate them from the natural Antarctic environment.

Distribution over time

There has been a high degree of variability in the rate of reporting of non-native species occurrences over the past 80+ years since non-native species were first observed in Antarctica (Fig. 3a). The peak in the 1960s coincided with a series of transplantation experiments by researchers from the British Antarctic Survey at Signy Island, South Orkney Islands (Edwards and Greene 1973; Edwards 1980). The smaller peak from c. 2009 to 2017 coincided with increased survey effort that resulted from the profile given to non-native species issues following the International Polar Year 2007/08 project 'Aliens in Antarctica' (Chown et al. 2012) and, most notably, the survey by German researchers of soil microfauna at visitor locations around the western Antarctic Peninsula (Russell et al. 2013; it is appropriate to note that this is an institutional report and not a formally reviewed literature article). Indeed, most of the Arachnida and Collembola reported during the 2010 and 2011 'spike' were the result of the latter study and illustrate the information that can be generated if targeted research effort is funded (Fig. 3b). Identifying non-native invertebrates demands high levels of taxonomic expertise and the efforts made during the period 2009–2017 have not been repeated since. Since c. 2017, the number of new reports has been low, with most new records being of non-native insects living synanthropically within research station facilities.

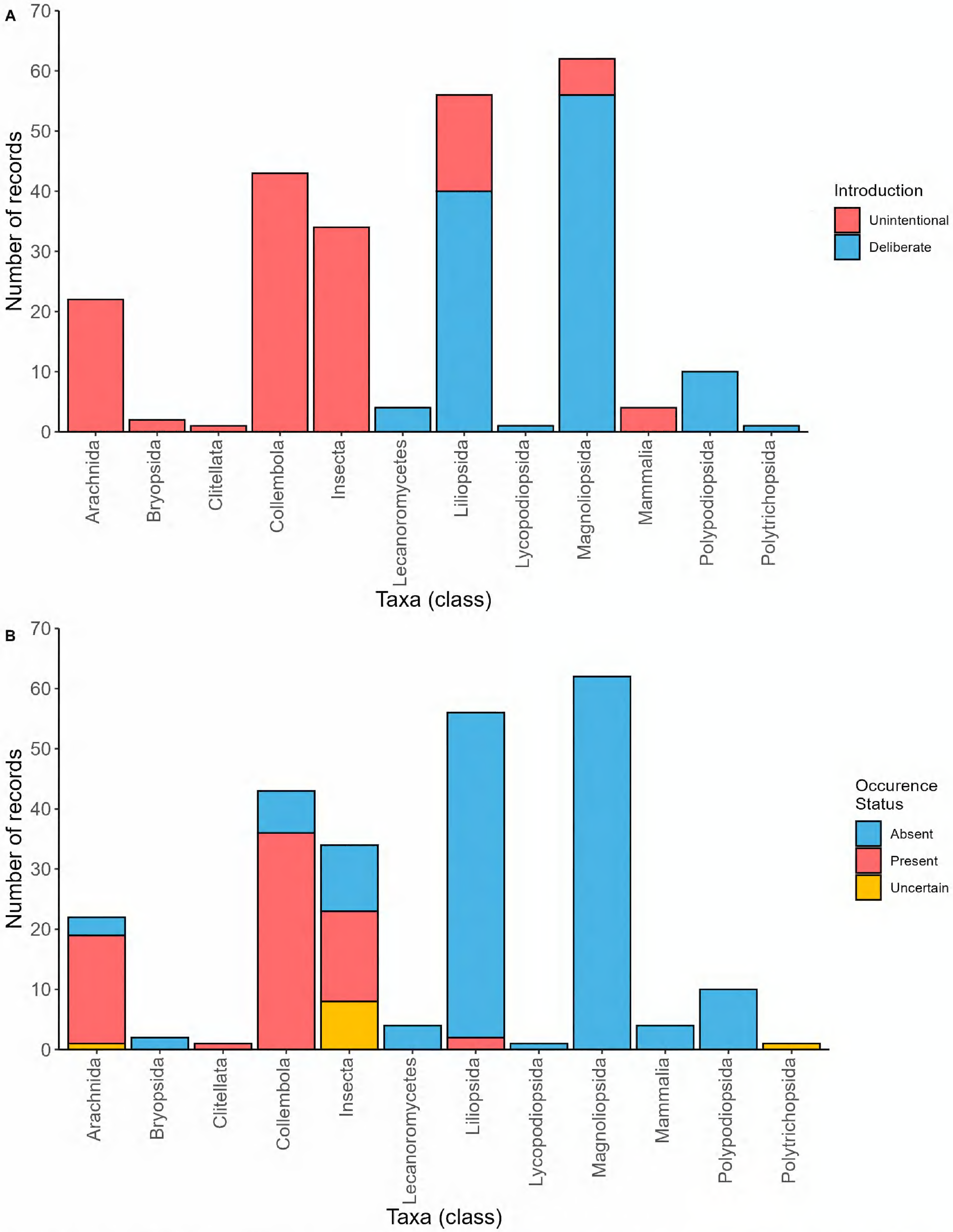

Figure 2. Number of records of different non-native species categorised to the taxonomic level of class that have established at different locations within the Antarctic Treaty area **A** data sub-divided based upon whether the introduction was deliberate or unintentional **B** data sub-divided based on the reported species' current occurrence status (absent/present/uncertain) in Antarctica.

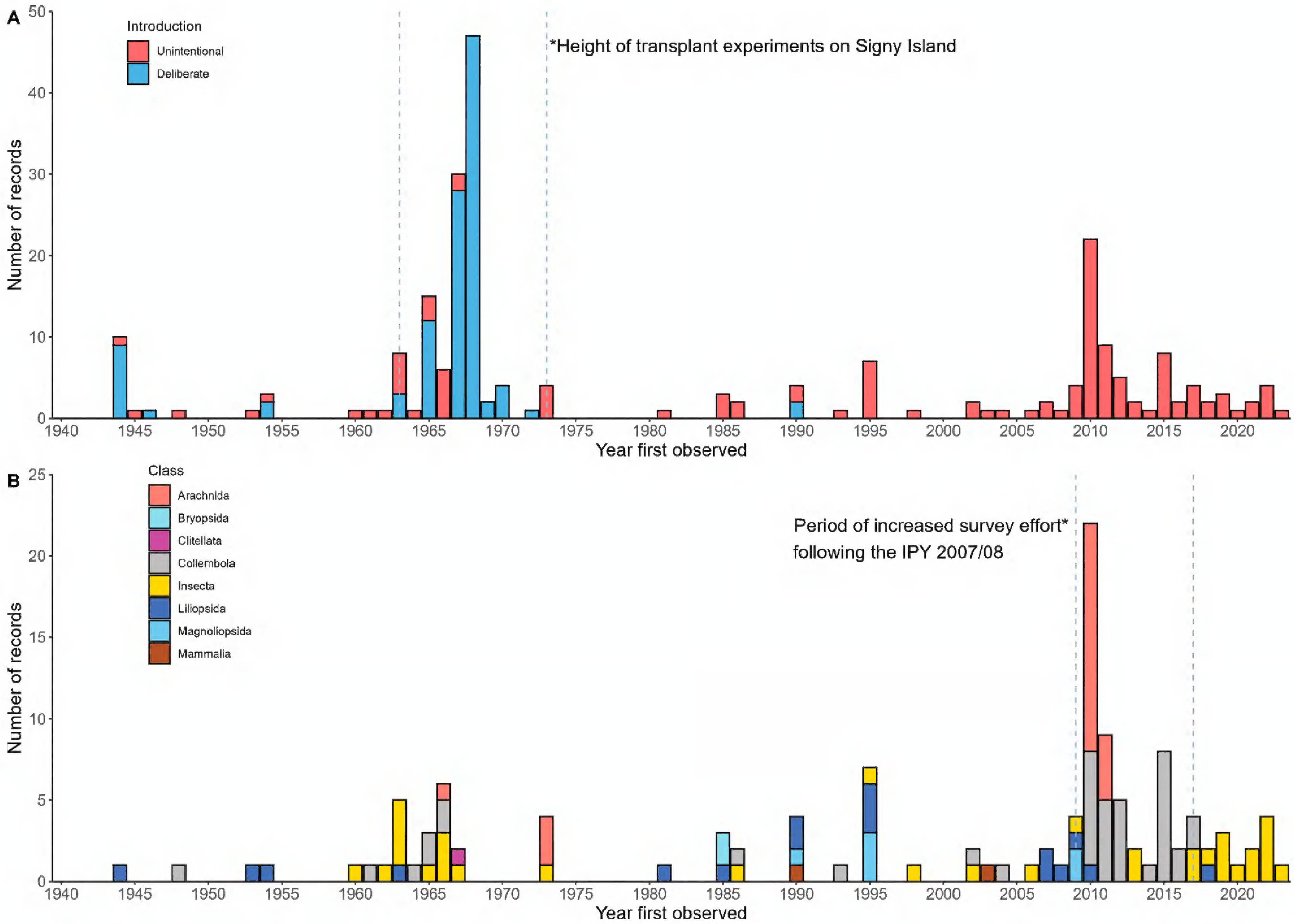

Figure 3. The year each reported non-native species occurrence was first observed in new locations within Antarctica (the three records from before 1940 are not displayed) **A** records classified by whether the introduction was deliberate or unintentional **B** records classified by taxonomic class of the species. Only records of species that were introduced unintentionally are included in B (therefore excluding the experimental introductions).

Association with human activities

The presence of Antarctic infrastructure increases the likelihood that non-native species will be found in the local vicinity. For example, c. 70% of reported non-native species existed either synanthropically within a research facility or had established within 1 km of infrastructure (Fig. 4). Of the species found in the natural environment, but within 1 km of research infrastructure, c. 75% were deliberate transplantation experiments that were subsequently removed (as were c. one third of reports found 5–10 km from infrastructure). Records of non-native species are also likely to be found near visitor landing sites commonly used by the tourism industry, with 85% of records (excluding synanthropic records) located within 1 km of a visitor site (recognising that a number of such sites are also close to research stations or foci of scientific research).

Fig. 5 shows the mean distance to the ten nearest biodiversity records for each non-experimental introduction and gives an impression of the survey effort at, and biodiversity knowledge of, each location. Smaller mean distances indicate a higher density of biodiversity records (and thus surveys and research undertaken at that location). The mean distance for biodiversity records in the biodiversity database (Terauds et al. 2025) to their ten nearest neighbours was 1.35 km. In comparison, over 90% of non-native species reports had ten biodiversity

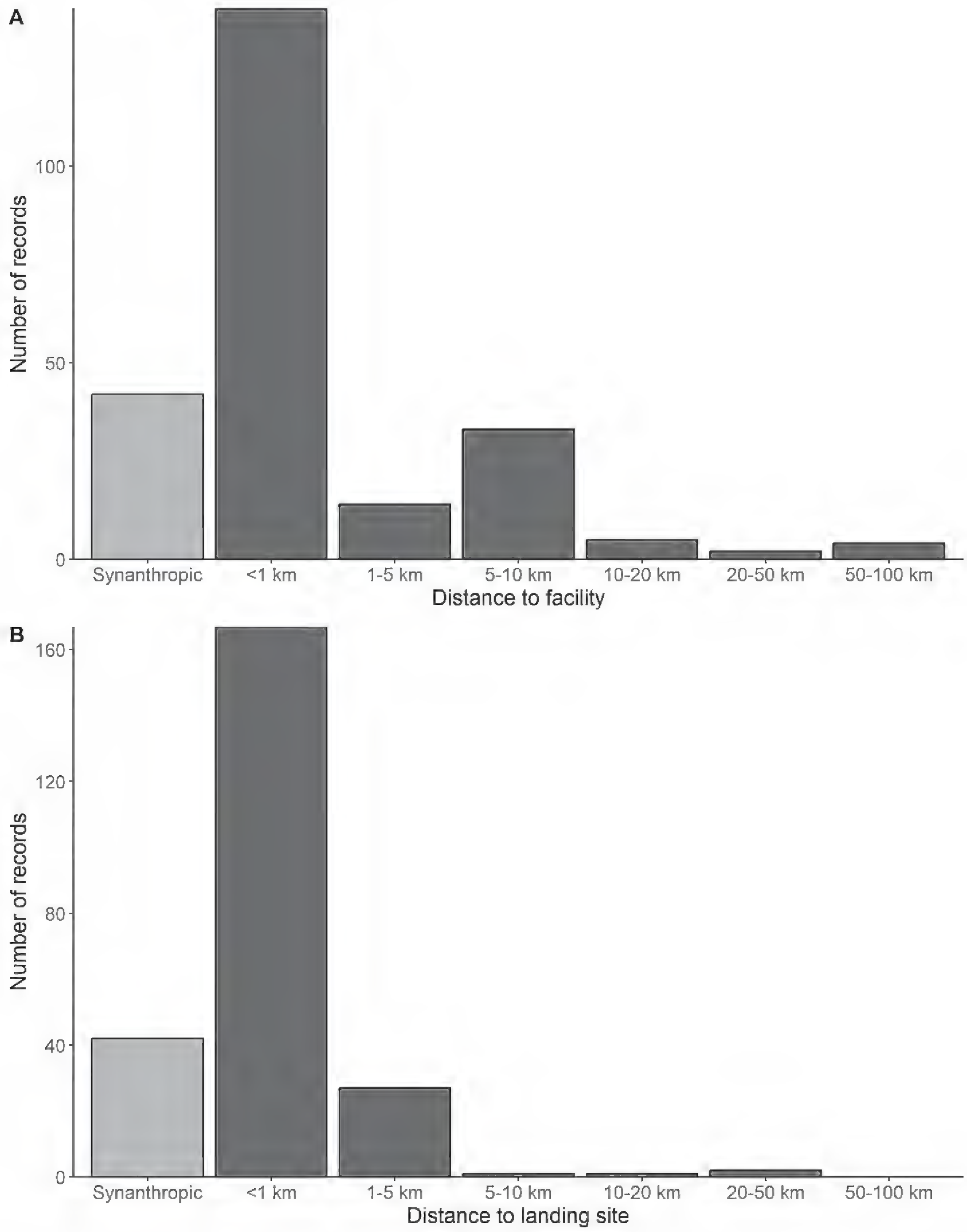

Figure 4. Distance of location of each non-native species record to **A** the nearest national Antarctic operator facility (e.g., research station, camp, airstrip, etc.), and **B** the nearest tourist landing site. Records classed as being located within Antarctic operator infrastructure (synanthropic records) are coloured light grey and labelled as 'Synanthropic'. Tourist landing sites can include national operator facilities, thus there are also synanthropic records included in (**B**). Records listed as < 1 km to facilities/landing site are in the vicinity of the infrastructure but are not inside it as such record would be classified as 'synanthropic'.

records within 700 m. These data indicate there has been a high level of survey effort at most locations where non-native species are detected, as could be anticipated given the close proximity of many records to research infrastructure (see Fig. 4). These data could reflect that non-native species are more likely to be detected in areas where there have been more biodiversity surveys and/or that they are more likely to be introduced at sites of high human activity. The higher density of biodiversity records near recorded non-native species could also indicate more suitable conditions for the establishment of native biodiversity more generally. However, it also highlights the dearth of both native and non-native biodiversity information from locations more distant from stations/visitor sites which, in the absence of data, make it impossible to know the extent of non-native species colonisation and distribution.

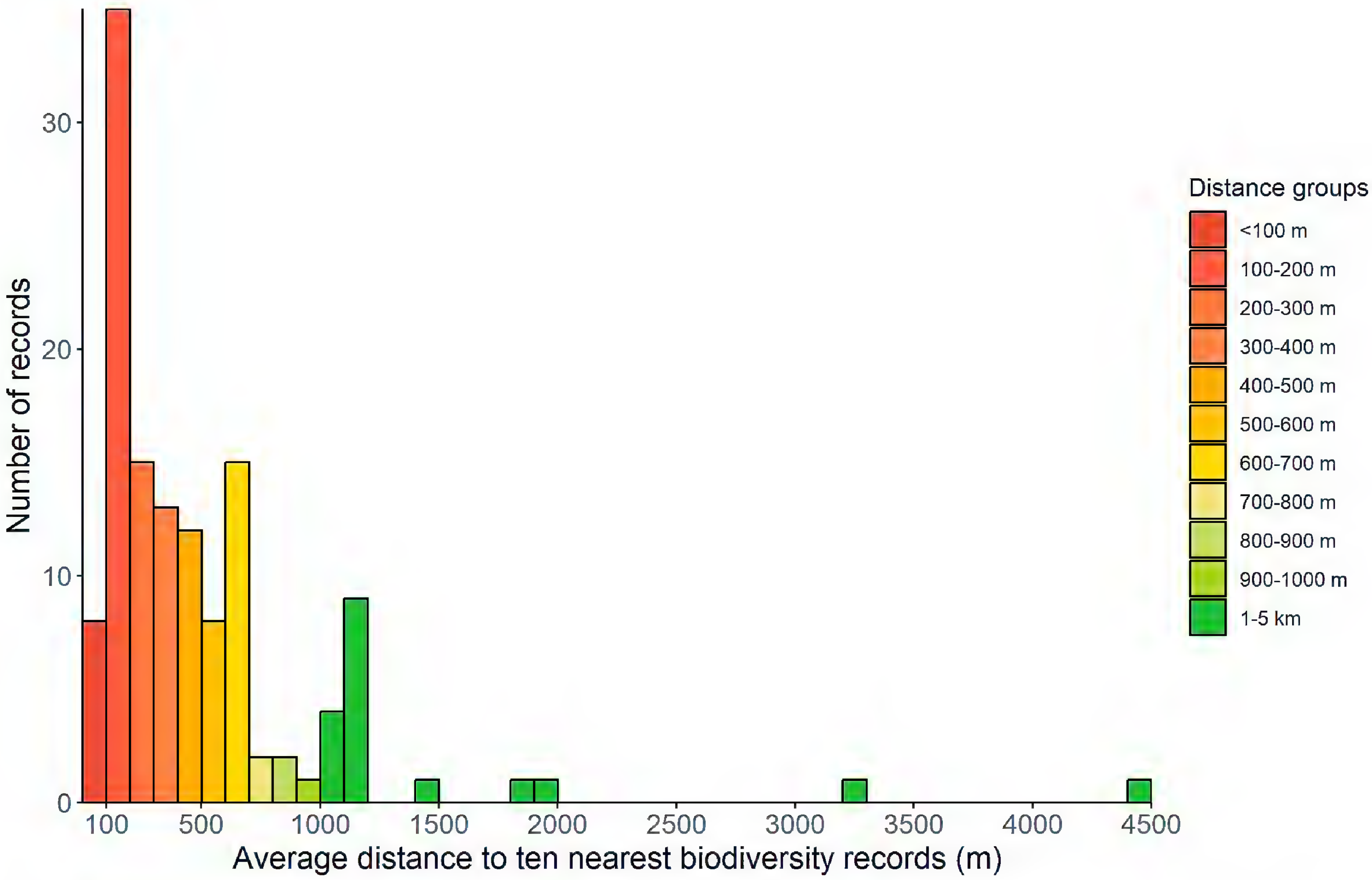

Figure 5. Average distance for each non-native species record location to the ten nearest biodiversity record locations. Only records classed as non-experimental introductions were included. The distance serves as a proxy of survey effort and biological knowledge of the site, where we assume that closer distances and higher densities mean that more research has been undertaken at the site.

Maximum survival time for currently present species

There are 20 species reported as currently present within the Antarctic Treaty area (Fig. 6), with some reported from more than one location (e.g., the springtail *Hypogastrura viatica* has been reported from 21 locations, more than any other Antarctic non-native species, albeit that many of these are from different parts of the same island, Deception Island). From Fig. 6 it can be seen that all established Antarctic terrestrial non-native species, except *P. annua*, are invertebrates, almost one third have been present in Antarctica for more than 50 years, and almost all have been present for more than 10 years. Only *P. annua* has been subject to any eradication efforts in the natural environment since it was first reported in the mid-1980s. More generally, apart from some species introduced during transplantation experiments, there are very few instances of established non-native species populations dying out without human intervention (although see Smith and Richardson (2011) and Hughes et al. (2017)).

Discussion

The introduction of non-native species, a proportion of which are likely to become invasive, presents one of the greatest threats to Antarctic terrestrial biodiversity today (Convey 2011; Convey and Peck 2019). Climate change, itself recognised as a global threat to biodiversity (but also, in isolation, likely to benefit in the short- to mid-term many native Antarctic terrestrial biota (Convey 2011; Lee et al. 2022b)) is also likely to exacerbate the threat of invasive species by increasing the likelihood

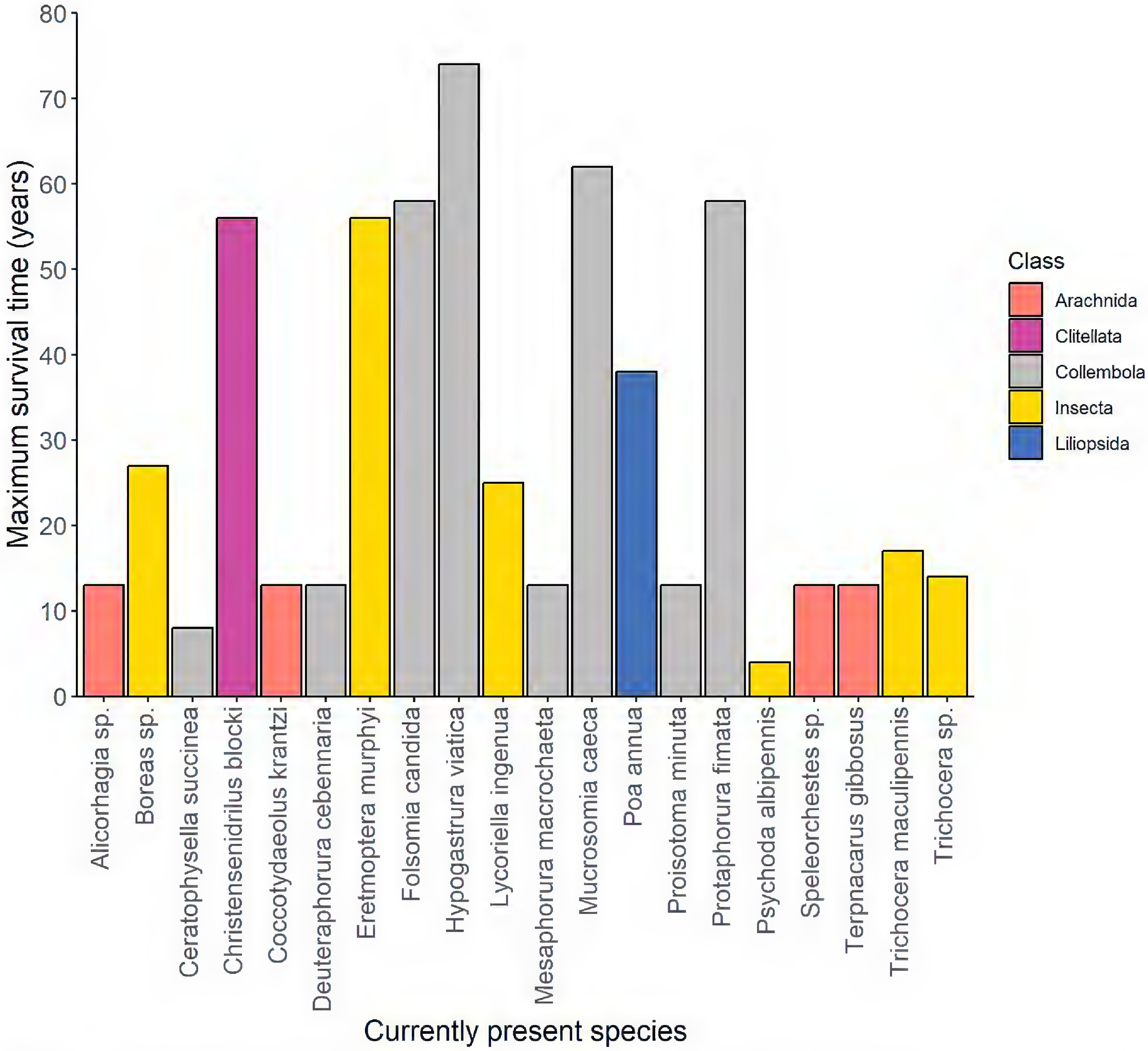

Figure 6. Maximum survival time of species currently known to be present within the Antarctic Treaty area.

of establishment (Chown et al. 2007; Beet et al. 2022; Siegert et al. 2023). The availability of datasets detailing non-native species introduction and establishment events is critical for policymakers to understand the scale of the risk and undertake appropriate policy responses (Hughes and Convey 2014; Hughes and Pertierra 2016; Antarctic Treaty Secretariat 2019; Remedios-De León et al. 2021).

Species introduced deliberately to the natural Antarctic environment during transplantation experiments

By far the largest group of records in our dataset related to the historical experimental introduction of plants from locations generally, but not always, beyond the Antarctic Treaty area in order to assess their survival under Antarctic conditions (Fig. 3a; for an overview, see Smith 1996). The longest experiments involving the greatest number of species were conducted by researchers from the British Antarctic Survey in ground adjacent to Signy Research Station, South Orkney Islands, during the 1960s and 1970s (e.g., Edwards and Greene 1973; Edwards 1980).

Some species transplanted from sub-Antarctic South Georgia, including *Acaena magellanica*, *A. tenera*, *Achillea millefolium*, *Phleum alpinum* and *Ranunculus repens*, survived for four years and some could likely have persisted for longer had they not been removed at the end of the experiment (Edwards 1980). Transplantation experiments have sometimes resulted in unintended consequences, with *P. pratensis*, at Cierva Point, and *E. murphyi* and *C. blocki*, at Signy Island, all being introduced in soil from beyond Antarctica and persisting long after the deliberately transplanted species were removed (Corte 1961; Burn 1982; Block and Christensen 1985; Dózsa-Farkas and Convey 1997; Pertierra et al. 2013, 2017b). Experimental transplantation of non-native species into the Antarctic natural environment has seldom if ever been undertaken in recent years (Fig. 3a), although transplantation experiments of native mosses over very short distances (a few tens of metres) have been done to assess the potential use of this method to minimize anthropogenic environmental damage in Antarctica (Câmara et al. 2021)

Non-experimental introductions of non-native species to the Antarctic natural environment

Our dataset shows that all non-native species thought to currently have reproducing populations in the natural environment in Antarctica are located in the western Antarctic Peninsula, South Shetland Islands and South Orkney Islands (generally known as the maritime Antarctic and incorporating the area covered by Antarctic Conservation Biogeographic Regions 1, 2 and 3; Terauds and Lee 2016; Fig. 1). Within this area, the most invaded location is Deception Island, where a combination of high human activity by the historical whaling industry, national operators and the tourism industry, plus the local presence of geothermally heated soils, generates an enhanced opportunity for species introduction and establishment (Greenslade et al. 2012; Hughes et al. 2015; Enriquez et al. 2019). Of the non-native species within Antarctica, *P. annua* on King George Island and *E. murphyi* on Signy Island might most reasonably be termed 'invasive' species, as defined by the CEP Non-native Species Manual ("non-native species that are extending their range in the colonised Antarctic region, displacing native species and causing significant harm to biological diversity or ecosystem functioning") (Antarctic Treaty Secretariat 2019). *Poa annua* has resisted on-going eradication efforts, probably because a seed bank is now present in the soil of Thomas Point near Arctowski Station (Galera et al. 2021; Poland 2024b). The persistence of this grass is of particular concern due to laboratory and field experimental studies that have concluded it can potentially outcompete the native higher plants (*Colobanthus quitensis* and *Deschampsia antarctica*), particularly under predicted climate change scenarios (Molina-Montenegro et al. 2019). Further research to understand the physiological limits of invasive species may allow future management attention to be focussed on particular regions and introduction pathways (see Duffy et al. 2017; Escribano-Álvarez et al. 2023). *Eretmoptera murphyi* is now accelerating in its spread from its original introduction site near Signy Research Station and may be responsible for a step change in increasing nutrient availability in local soils (Hughes and Worland 2010; Bartlett et al. 2020, 2023). Although the distribution of *E. murphyi* is currently restricted to a relatively small part of Signy Island, there are concerns that any further dispersal, by natural or anthropogenic means, could have substantial impacts upon terrestrial habitats and potentially the closely related

endemic Antarctic fly *Belgica antarctica* across the western Antarctic Peninsula region (Hughes et al. 2013; Bartlett et al, 2021)

The only species occurrences in this group that have been eradicated or have had eradication attempts undertaken on them are plants. In some cases, considerable efforts have been taken to eradicate non-native plants (with mixed success) but, as far as we are aware, no effort has been made to eradicate or control non-native invertebrates beyond research facilities, even if they have often been known to be present at these sites for more than 10 years (Fig. 6). The lack of invertebrate eradication attempts in the natural environment is largely because the technology to do so has not been sufficiently developed and pesticide use for environmental management purposes is not listed as a legitimate use within the Environmental Protocol (Hughes and Pertierra 2016; Galera et al. 2017, 2021). Most efforts to eradicate *P. annua* within the Treaty area have involved the removal of single or small numbers of specimens from the vicinity of research stations or other sites by visiting researchers (Molina-Montenegro et al. 2012, 2014; Malfasi et al. 2020). In contrast, a vegetatively expanding patch of *P. pratensis* that was located on Cierva Point for almost six decades was eradicated by an international team of researchers over several days and involved the removal of over 500 kg of soil (Pertierra et al. 2013, 2017b). Annex II to the Environmental Protocol states that introduced non-native species shall be removed "unless the removal or disposal would result in a greater adverse environmental impact" (Article 4(5)); however, it may prove challenging to predict the potential impact of an introduced non-native species and adoption of a precautionary approach with the removal of the non-native species is likely to be the best approach (Hughes and Pertierra 2016).

Deciding the correct course of action when considering the removal of a newly discovered plant may not be straightforward. In early 2009, *G. nivalis* and *N. magellanica* were reported from Deception Island and the authors, KAH and PC, visited the location to assess the situation the following season (Smith and Richardson 2011). During the intervening period, the *G. nivalis* plants had been washed away by ephemeral streams; however, a single healthy specimen of *N. magellanica* remained, clearly several years old. Given that both species are native to Tierra del Fuego, it was not clear if the species' presence was a result of a natural colonisation event (in which case any plants should be protected), or an anthropogenic introduction event (in which case any plants should be eradicated) (see discussion in Hughes and Convey 2012). In the end, the remaining *N. magellanica* plant was removed as an example of application of the precautionary principle but, in the absence of any other evidence relating to the introduction or establishment event, it remains unclear whether or not the correct course of action was applied. Not least, a sole criterion of 'remove if close to an area of human activity' is inappropriate or simplistic, as it would likely apply to virtually all ice-free areas in the South Shetland Islands, the part of Antarctica closest to the nearest source of colonisers in southern South America and also the mildest part of Antarctica, hence the most likely to be successfully colonised by incoming natural propagules.

Non-experimental introductions of non-native species persisting synanthropically

Forty-one reports concerned at least 22 species that have been or continue to be present synanthropically in research stations and other human facilities. Even though there are few explicit records, we acknowledge that rats and mice have

probably been introduced to Antarctica on multiple occasions by historical shipping and industrial operations, as well as early in the phase of research station development (Headland 2012) but have not survived. Today, enhanced hygiene practices and waste management means that opportunities for rodent establishment, if introduced, are likely to be much reduced. Many of the invertebrate species recorded have been associated with greenhouses and hydroponic facilities on Antarctic research stations (e.g., Bergstrom et al. 2018). Numerous reports of spiders, dipterans, collembolans and psocids in such facilities exist, but formal identification to species level has been relatively uncommon (Greenslade 1987; Smith 1996; AAD 1998; Bamsey et al. 2015). Such synanthropic establishments may be expected given the high rates and diversities of invertebrate introductions recorded at some stations located across Antarctica (Chwedorzewska et al. 2013; Houghton et al. 2016; Newman et al. 2018). Sewage treatment plants have also been subject to increasing reports of non-native species introductions with *Lycoriella ingenua* at Casey Station and *T. maculipennis* (and most recently *Psychoda albipennis*) recorded at an increasing number of treatment plants on King George Island, South Shetland Islands (Hughes et al. 2005; Volonterio et al. 2013; COMNAP 2019; Korea and Chile 2022; Hernandez-Martelo et al. 2024). Emerging reports that *T. maculipennis* is reproducing in the natural environment and the potential human-mediated or natural movement of this winged species to other Antarctic locations are major causes for concern and there now appears to be similar potential for *P. albipennis* (Potocka and Krzeminska 2018; Hughes et al. 2019; Remedios-De León et al. 2021; Hernandez-Martelo et al. 2024; Kang et al. 2024; Poland 2024a).

Status developments in the past decade

Since the publication of Hughes et al. (2015) details of 39 new records of non-native species observed across the continent have been published. All but two of these are from the South Shetland Islands and 21 are new Collembola records from targeted surveys by Enríquez et al. (2018; 2019) at different sites on Deception and Barrientos Islands. One of the new records is for *P. annua*, where a clump of two individuals was discovered on the Gourlay Peninsula on Signy Island (Malfasi et al. 2020). The clump was removed several days later in accordance with Annex II to the Protocol on Environmental Protection to the Antarctic Treaty. The clump was located more than 2 km from Signy Island research station (the closest facility, and also with no evidence of the species being present), suggesting the species may have reached this location via non-assisted dispersal in the region (Malfasi et al. 2020). Given the potentially drastic impacts *P. annua* could have on the environment, rapid detection and removal is essential, although such opportunistic observations also highlight the general lack of detailed expert survey effort across the entire region and, hence, lack of explicit knowledge of unsurveyed areas. One new record is for the synanthropic Collembolan, *Xenylla* sp., which was subsequently eradicated from hydroponic facilities on Davis Station, East Antarctica (Bergstrom et al. 2018). Thirteen records are for confirmed synanthropic insects (all Lepidoptera or Diptera). Of these, three are for the Indian meal moth (*Plodia interpunctella*) and one for the Mediterranean flour moth (*Ephestia kuehniella*), detected in three different research stations on King George Island and one further south at Yelcho Station on Doumer Island (Câmara et al. 2022; Benitez et al. 2024). All individuals seen were eradicated (or presumed eradicated), although this has not been

confirmed. Two other records concerned the moth *P. albipennis*, whose increasing distribution on King George Island would benefit from further research to understand if the species can reproduce in the natural environment (Korea and Chile 2022; Hernandez-Martelo et al. 2024). While some earlier records of *T. maculipennis* are non-synanthropic but with no evidence of reproduction in the natural environment (e.g., Volonterio et al. 2013), six recent synanthropic records are for the fly having colonised station sewage treatment plants. One additional new record for *T. maculipennis* was within a refuge hut in ASPA 132 (before it was promptly eradicated), more than 9 km from its closest currently established population at King Sejong station (Korea et al. 2016; Remedios-De León et al. 2021; Argentina and Uruguay 2022). A recent non-peer-reviewed paper submitted to the CEP recorded *T. maculipennis* at several locations within ASPA 128 Western Shores of Admiralty Bay (Poland 2024a). At one location within the ASPA, Llano Point, the presence of larvae and pupae in the vicinity of penguin colonies indicated that the fly can survive and reproduce beyond station confines. If accurate, this is probably the largest and most concerning non-native species development within the past decade (Remedios-De León et al. 2021). The continued expansion of *P. annua* at Thomas Point into areas of native plant communities, despite substantial eradication efforts, is the other major concern (Poland 2024b).

Developments in non-native species policy and response

Up until the end of the first decade of the 21st century, targeted survey effort to identify non-native species was lacking, with most introduced populations identified by chance or during other survey work (Fig. 3). The issue of non-native species introductions and biosecurity received an increased profile within the ATCM following the publication of results of the International Polar Year 2007/08 'Aliens in Antarctica' research project (SCAR 2010; Chown et al. 2012; Huiskes et al. 2014). Subsequently, more targeted surveys were undertaken, particularly for non-native invertebrates in the vicinity of frequently visited sites, and new non-native populations were found (e.g., Russell et al. 2013; Enríquez et al. 2018, 2019). However, with the spread of large (relative to other native species), persistent and easily dispersed non-native species, such as *T. maculipennis* and *P. annua*, in the past decade or so, the issue of non-native species management and control/eradication has increased in profile (Hughes and Pertierra 2016; Remedios-De León et al. 2021). Some Parties have allocated resources to undertake research and initiate management and control of these species with varying degrees of success (Galera et al. 2017, 2019, 2021; Potocka and Krzeminska 2018; Kang et al. 2024; Korea 2024). However, in recent years, fewer specific surveys targeting new non-native species have been reported in the academic literature, and most reported introductions have been in the immediate vicinity of research stations or of species living within research facilities (Korea and Chile 2022; Benitez et al. 2024). It is possible that some Parties may be using their available budgets to manage existing non-native species with monitoring for new species consequently falling down the priority list. Nevertheless, the association of established non-native species with national operator infrastructure and tourist visitor sites (Fig. 4) highlights the need for on-going and enhanced biosecurity precautions that are applicable to all human activities in the region. The CEP Non-native Species Manual identifies three

major components of a non-native species management framework: Prevention, Monitoring and Response, and all are essential if Antarctic environments are to be adequately protected. Assuming that governments allocate resources to their national Antarctic programmes to address non-native species issues, it may be a challenge to determine how best to divide this funding to deliver (i) effective biosecurity practices along the supply chain (Prevention), (ii) monitoring for new non-native species in Antarctica (Monitoring), and (iii) control and/or eradication of established non-native species and delivery of research to identify practical methods to respond to these introductions (Response). Nevertheless, in an Antarctic context, the CEP non-native species manual acknowledges that resources targeted towards prevention of species introduction and associated biosecurity measures deliver the greatest conservation benefit compared with other management responses (Antarctic Treaty Secretariat 2019).

It is notable that non-native plants have generally been eradicated, but the difficulty in delivering the full eradication of *P. annua* at Admiralty Bay is a major cause for concern, and it can only be hoped that Poland maintains its on-going efforts to control the grass (Galera et al. 2017, 2019, 2021; Poland 2024b). Also of concern is the almost universal failure of Parties to control or eradicate any non-native invertebrates that have established in the natural environment, with some of these species now having persisted in Antarctica for several decades. Investment in research to identify practical methods to respond to these introductions is urgently needed, although many such invertebrates may now be beyond any practical form of control, as has also been recognised for a number of non-native species on sub-Antarctic islands (e.g. South Georgia (Black 2022)).

Final remarks

The records presented here provide evidence regarding the number, diversity and spatial distribution of species introductions leading to short or long-term establishment in the Antarctic Treaty area. For most of the 19th and 20th centuries, precautions taken to prevent the introduction of non-native species were few or non-existent. Today, the Antarctic tourism industry, under the guidance of IAATO, generally employs extremely high standards of biosecurity, commensurate with their concerns for preserving the Antarctic environment and the image of organisational environmental awareness and responsibility that they wish to promote to their clients (IAATO 2023, 2024). National Antarctic programmes, in general, manage much more complex logistical operations in Antarctica than does the tourism industry and may struggle to achieve equivalent high standards across their range of operations. Further, it is also likely that levels of awareness of non-native species issues differ across national programmes, alongside the level of implementation of biosecurity measures, despite the best efforts of COMNAP and SCAR (COMNAP 2015; COMNAP and SCAR 2019). The CEP is responsible for providing advice to the ATCM on issues relating to non-natives species. However, in recent years, despite numerous papers by Antarctic Treaty Parties describing the challenges of addressing non-native species within the Treaty area (e.g., Poland 2024a, b), there have been few initiatives emanating from the CEP to further enhance biosecurity, or to understand how effectively national operators are implementing biosecurity measures, despite this being given high priority on the CEP Five-Year Work Programme (Antarctic Treaty

Secretariat 2024b). It is hoped that the information made available in this dataset (https://doi.org/10.5285/afeb9f5e-bd69-4e3d-9d50-e935134f4c78) and associated online application (https://saer-non-nativespecies.data.bas.ac.uk/) will demonstrate clearly the extent and increasing seriousness of the challenges created by non-native species in Antarctica and that accelerated policy development and management action will result (Lee et al. 2022b).

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Additional information

Conflict of interest

The authors have declared that no competing interests exist.

Ethical statement

No ethical statement was reported.

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Author contributions

KH: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data Curation, Writing - Original draft, Writing - Review and Editing. PC: Conceptualization, Methodology, Validation, Investigation, Writing - Original draft, Writing - Review and Editing. JL: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data Curation, Writing - Original draft, Writing - Review and Editing, Visualization.

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Data availability

All of the data that support the findings of this study are available in the main text.

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